23.5 A 4-Channel UWB Beam-Former in 0.13µm CMOS using a Path-Sharing True-Time-Delay Architecture

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Ultra-wideband (UWB) communication and imaging systems based on impulse radio (IR) have gained significant interest in a variety of commercial and military applications. The utilization of ultra short pulses in the time domain, corresponding to ultra-wide bandwidth in the frequency domain, increases the data rate and range resolution in wireless communication and imaging applications, respectively. For instance, an imaging system using the FCC designated 3.1 to 10.6GHz frequency range can achieve 2cm of range resolution in free space. In addition, the power consumption and cost of an UWB IR can be lower compared to its conventional narrowband counterparts due to simple detection schemes of UWB impulse signals.

Multiple antenna transceivers offer spatial diversity and increase the communication capacity. In imaging applications, a sequence of pulses are transmitted towards the target. The receiver collects the reflected and/or scattered signals in order to reconstruct the image. The azimuth resolution of an imaging system is proportional to the electromagnetic beam width. In order to achieve a high azimuth resolution over a large imaging area, the electromagnetic beam should be scanned, mechanically, or electronically by using phased arrays. Phased arrays function as electronically controlled spatial filters, improve the receiver SNR [1], and relax the power amplifier output power requirement [2].

UWB impulse radio and narrowband multi-antenna systems are fundamentally different. In narrowband multi-antenna systems, the time delay is often approximated with a constant phase shift over the bandwidth of interest [1]. This approximation fails for UWB systems. Unlike narrowband phased arrays, the array beam pattern of UWB IR beam-forming systems is a function of the signal waveform and the detection scheme [3]. The UWB IR beam pattern is inversely proportional to the signal bandwidth and the antenna spacing [3]. In summary, both range and azimuth resolutions of UWB IR beam-forming systems improve with more bandwidth, making them ideal candidates for high resolution imaging applications.

Each antenna element in a beam-former receives the signal at delayed time intervals depending on the incident angle. The antenna takes the time derivative of the incident UWB signal [4]. In conventional architectures, a variable true-time-delay element is required in each path of the UWB beam-former to compensate the propagation delay (Fig. 23.5.1). The time delay can be varied by routing the UWB signal through different lengths of on-chip transmission lines [3]. This implementation leads to a large chip area when large delays are required for extreme scanning angles.

In this paper, a fully integrated 4-channel UWB beam-former in 0.13µm CMOS is presented that uses a path-sharing true-time-delay architecture. The time-delay differences between adjacent channels in a beam-former are constant for any given incident angle. Therefore, the variable time delays can be configured in cascade so that the signals are combined locally after each delay element (Fig. 23.5.1).

The signal after each antenna element is delayed to match the signal in the adjacent path. For an n-channel beam-former, the maximum required delay for each variable-time-delay element in the path-sharing architecture is reduced by a factor of $n-1$ as compared to the conventional architecture. This leads to a significant reduction in the chip area.

The variable-delay elements are incorporated as a tapped-delay trombone line that is shared between all 4 channels (Fig. 23.5.2). The trombone line is implemented as a quasi-distributed differential transmission line that uses on-chip spiral inductors. A matrix configuration of UWB amplifiers allows for the selection of different path lengths in the shared-tapped-delay trombone line. For any incident angle $\alpha \neq 0$, only one column of these path-select amplifiers is turned on to provide equal delay difference between adjacent channels. Two path-select amplifiers with opposite input-output connections are used in parallel for full spatial coverage. Delayed signals are combined locally in current domain between adjacent channels. For the normal incident angle, $\alpha=0$, all the path-select amplifiers are turned off and the signals simply travel along the transmission lines to the output with equal delays as shown in Fig. 23.5.2. All signals are then combined coherently in an UWB active-power-combining section that uses quasi-distributed transmission lines.

The signal from each antenna element is amplified by a fully differential variable-gain UWB LNA (Fig. 23.5.3). The amplified signals are injected into the shared-tapped-delay trombone line in the current domain. The 100Ω differential input impedance is accomplished by using shunt-series feedback resistor R_f and a 3rd-order passive network that is constructed from the input pad capacitance, spiral inductor L_{s1}, and the total input gate capacitance of the amplifier. Shunt-peaking inductors are used to further enhance the bandwidth. The measured –3dB bandwidth and the gain of the stand-alone UWB LNA are 18GHz and 10dB, respectively. The LNA gain can be varied by 5dB in 1dB steps by changing the tail bias current of the second-stage differential pair. A dummy stage maintains constant DC current for all gain settings. The variable gain option allows compensating for possible path-loss differences between different channels. The UWB LNA achieves a measured noise figure of 2.9 to 4.8dB across the 18GHz bandwidth with less than 5ps of group-delay variation.

Each path-select UWB amplifier is a fully differential 2-stage design (Fig. 23.5.3). The layout of the matrix configuration in the 4-channel beam-former necessitates long interconnects to the path-select amplifiers. The inductance and mutual coupling of these interconnects, implemented as stacked slab inductors, are exploited to enhance the bandwidth [3]. Note that only one of the path-select amplifier pairs in Fig. 23.5.3 is turned on for a particular incident angle. The amplifiers in the UWB active power combiner also use a similar topology. The appropriate state for the beam-former is loaded into on-chip shift-registers via a computer interface.

The 4-channel UWB beam-former is implemented in a 0.13µm CMOS technology (Fig. 23.5.7). The process offers 2 thick metal layers that are used to implement on-chip spiral inductors and transmission lines. The chip produces a true-time-delay resolution of 15ps and 11 different scanning angles. The measured bandwidth of the beam-former for the normal incident angle is 18GHz (Fig. 23.5.4). The bandwidth is reduced to 12GHz as the signal travels through the longest path corresponding to a larger scan angle. The total array gain and SNR are improved by 12dB and 6dB (theory), respectively, compared to the performance of individual channels, due to the coherent addition of signals and incoherent addition of uncorrelated noise sources. The UWB antenna patterns, assuming correlation detection for a second derivative of a Gaussian impulse and an antenna separation of 2.5cm are shown in Fig. 23.5.5. The chip demonstrates ±60° beam steering with 10° spatial resolution. Figure 23.5.6 summarizes the 4-channel UWB beam-former measurement results.

Acknowledgements:
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References:
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[3] Jonathan Roderick, H. Krishnaswamy, K. Newton, and H. Hashemi, “Silicon-Based Ultra-Wideband Beam-Forming,” *IEEE J. Solid-State Circuits*, vol. 41, pp. 1726-1739, Aug., 2006.
[4] I. Immoreev and D.V Fedotov, “Ultra Wideband Radar Systems: Advantages and Disadvantages,” *UBW Systems and Technologies Dig. Papers*, pp. 201-205, May, 2002.

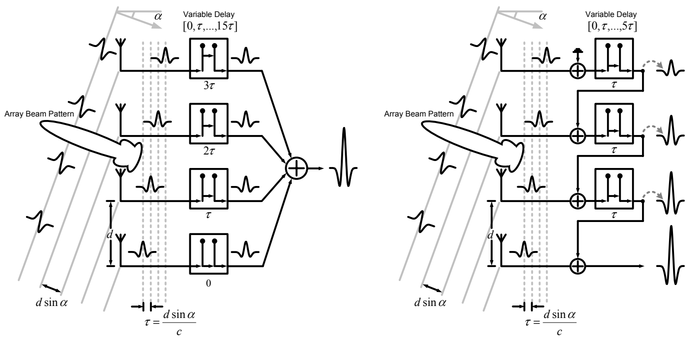

Figure 23.5.1: Conventional UWB beam-former and the proposed path-sharing UWB beam-former.

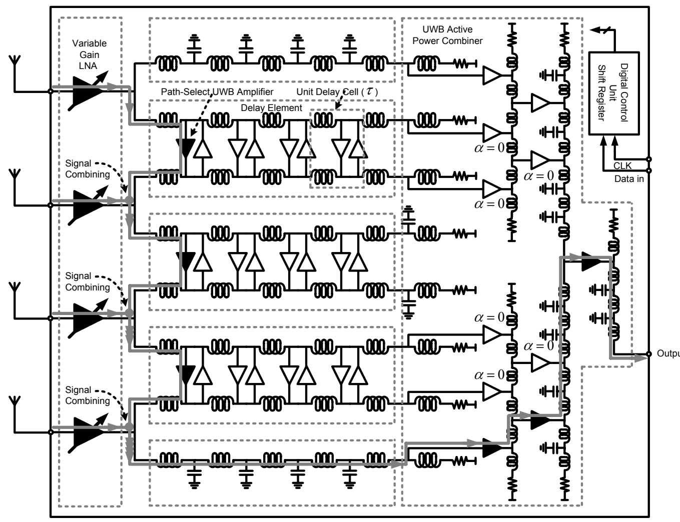

Figure 23.5.2: Block diagram of the path-sharing UWB beam-former and signal flow corresponding to one incident angle. Single-ended version is shown for simplicity.

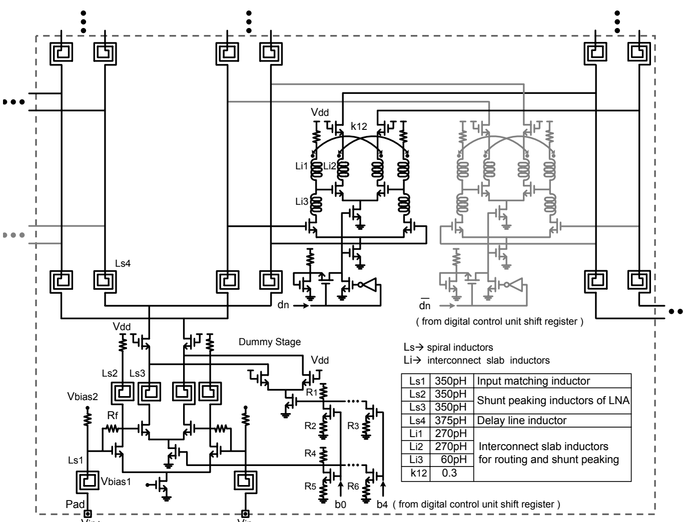

Figure 23.5.3: Schematic of the UWB front-end and the path-select UWB amplifier (one path).

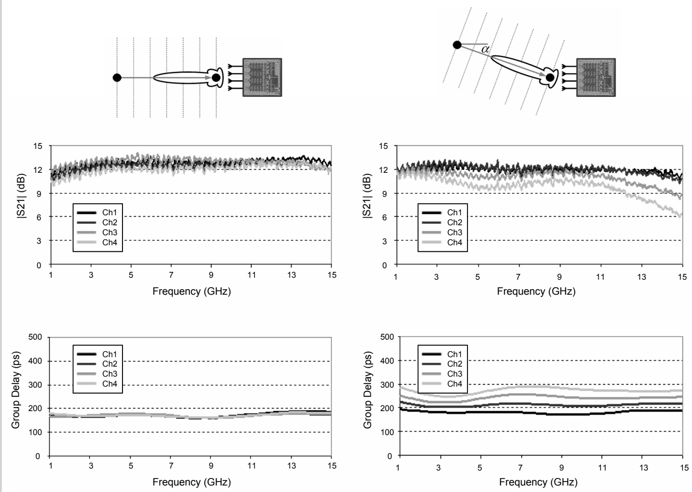

Figure 23.5.4: Measured magnitude response and group delay of all channels for two incident angles.

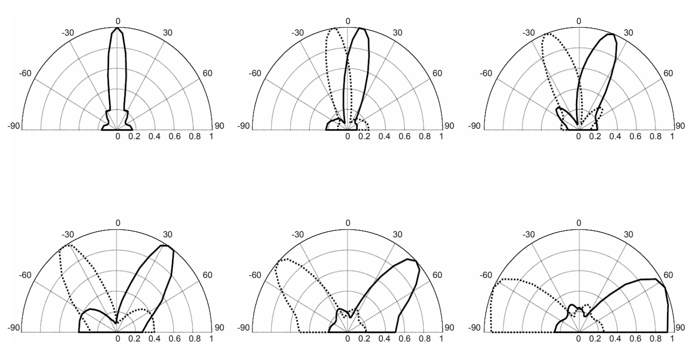

Figure 23.5.5: Measured UWB normalized array patterns for secondderivate Gaussian impulse signal.

UWB Front-End

-3dB Bandwidth	18GHz
Power gain	10dB
Noise-Figure (1GHz – 18GHz)	2.9 dB – 4.8dB
Programmable gain	5dB in 1dB steps
Group delay variation	< 5ps
Power dissipation	40mA @1.5V

Complete 4-Channel UWB Beam-former

-3dB Bandwidth (normal incident angle)	18GHz
Total array gain	24dB
SNR improvement (theory)	6dB
UWB true time delay resolution	15ps
Beam steering spatial resolution	10° (antenna separation = 25mm)
Maximum beam steering spatial angle	60° (antenna separation = 25mm)
Total number of available beams	11 (3.5bits)
Power dissipation@1.5V	370mA
Total number of on-chip spiral inductors	188
Technology	0.13µm CMOS
Die Area	3.2mm x 3.1mm

Figure 23.5.6: 4-Channel UWB beam-former measured performance summary.

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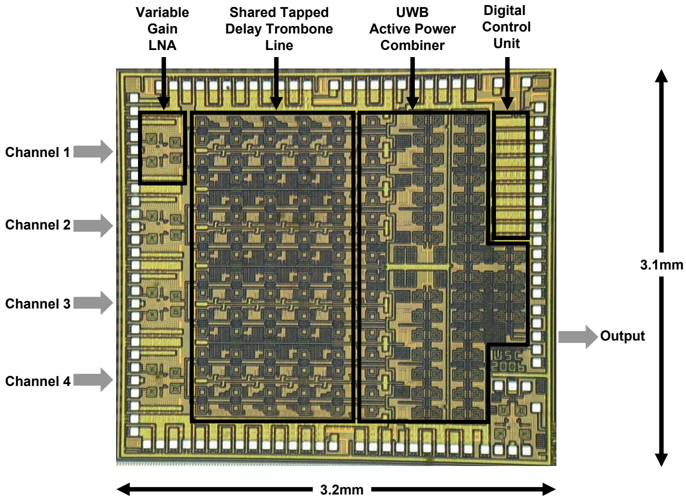

Figure 23.5.7: Chip micrograph of the 4-channel UWB beam-former.

